THE CALIFORNIA STATE UNIVERSITY MOBILE ATMOSPHERIC PROFILING SYSTEM

A Facility for Research and Education in Boundary Layer Meteorology

by Craig B. Clements and Andrew J. Oliphant

A new, highly portable, fast-deploying atmospheric profiling system has been developed to allow researchers and students new measurement opportunities.

Experimental research in boundary layer meteorology is critical for improving our understanding of surface–atmosphere interactions. Investigations of problems such as wildland fire–atmosphere interaction, ecosystem and urban micrometeorology, marine-layer fog transport processes, and wind energy assessment require information on atmosphere structure and processes in the surface layer and profiles of meteorological parameters in the lowest 2,000 m of the atmosphere. Obtaining detailed, in situ observations of boundary layer characteristics is difficult because these studies frequently require measurements at very specific locations and times and frequently in locations where there is limited infrastructure to support measurements. Detailed boundary layer measurements are also very expensive to make with a large part of the cost coming from instrumentation and infrastructure. The availability of experimental equipment also has important implications for teaching in universities, with the need to provide hands-on learning experiences in field-based measurements as early as possible for future boundary layer researchers (Takle 2000). This point is particularly salient for the large population of U.S. university students who are not studying at major research universities and for the large population who are currently underrepresented in the atmospheric sciences.

Mobility of measurement platforms is a typical requirement for many atmospheric phenomena. While there is an advantage of fixed towers and profiling platforms, mobile platforms offer the ability to seek or chase the phenomenon (Biggerstaff et al. 2005). For example, to study severe weather and thunderstorm dynamics, the National Severe

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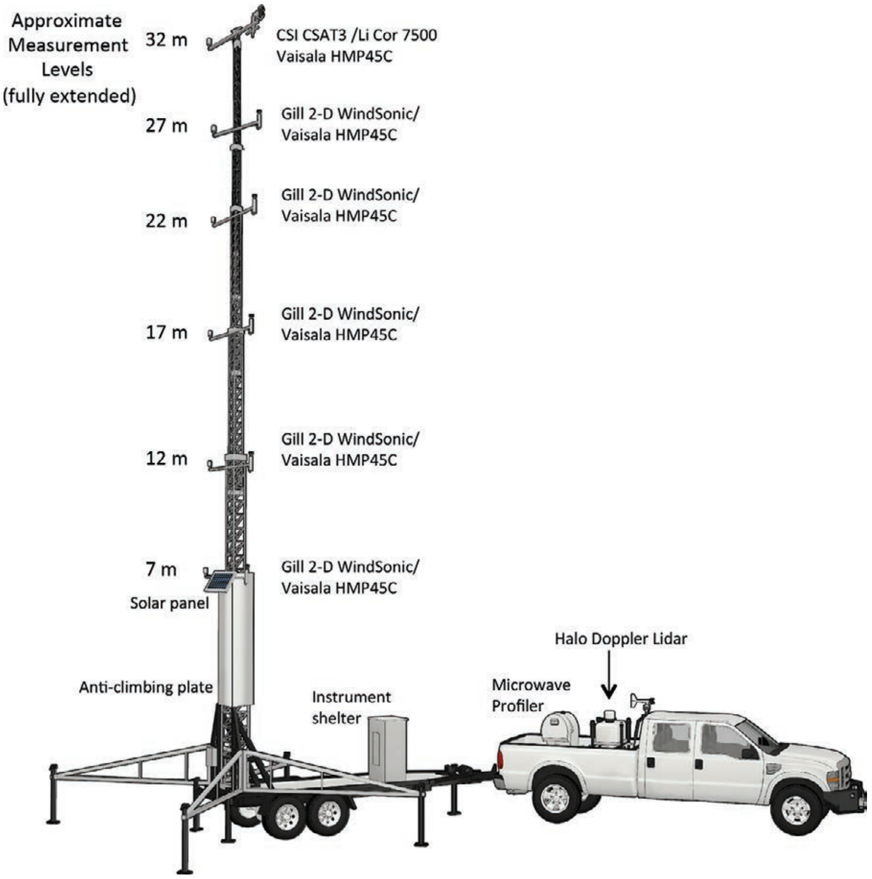

Fig. 1. Idealized schematic diagram of CSU-MAPS configuration and components.

Storms Laboratory (Straka et al. 1996) developed a mobile mesonet based on a suite of standard weather station sensors modified for use on a moving vehicle such as a car. These mobile mesonet platforms have become very popular in severe weather research (Taylor et al. 2011).

While there are mobile radar platforms jointly managed by federal agencies and universities throughout the United States [e.g., the Shared Mobile Atmospheric Research and Teaching radar (SMART); Biggerstaff et al. 2005], there are few rapid-response, comprehensive mobile boundary layer profiling systems available to researchers at universities. One such system is the University of Alabama in Huntsville Mobile Integrated Profiling System (MIPS). The MIPS was developed for observing both boundary layer phenomena and storm dynamics (Karan and Knupp 2006). The MIPS has been deployed successfully during many major field campaigns demonstrating the utility of mobile profiling systems in atmospheric research (Knupp 2006). Similar systems have been developed by the National Center for Atmospheric Research, the Mobile Integrated Sounding System (MISS) (Cohn et al. 2004), and by the University of Manitoba (Taylor et al. 2011). Microwave temperature profilers have also been used in a mobile application by being mounted in a car or similar vehicle (Khaikine et al. 2005). One lacking feature of these mobile profiling systems is the ability to measure the atmospheric surface layer in situ while simultaneously measuring the boundary layer and upper troposphere. To overcome this limitation, a new mobile atmospheric profiling system has been developed.

In this article we describe the California State University Mobile Atmospheric Profiling System (CSU-MAPS), a mobile measurement system designed to be a shared resource to support the research of multiple investigators in the California State University system and beyond, to help solve a wide range of boundary layer research questions, and to provide a mobile teaching laboratory for technical learning. In the following sections we discuss the details of the measurement platforms and instruments, provide examples of research projects illustrating the system capabilities, and discuss the pedagogical advantages of CSU-MAPS.

SYSTEM DESIGN AND INSTRUMENTATION. CSU-MAPS is comprised of two mobile platforms, an instrumented 32-m micrometeorological tower and a 3/4 ton (~910 kg), 4 × 4 pickup truck with mounted instruments including a scanning Doppler lidar, microwave profiling radiometer, and two upper-air sounding systems (Fig. 1). The entire system can be rapidly deployed and left unattended in a wide variety of environments and conditions (Fig. 2). A summary of the instrumentation and sensors is provided in Table 1.

Surface-layer measurements. The atmospheric surface layer, the lowest 10% of the atmospheric boundary layer (ABL), is characterized by strong gradients of wind speed, temperature, water vapor, and trace gasses, which change dynamically in response to surface forcing. Because of the heterogeneity of the surface and the potential impact of individual surface elements on the measurement, finding ideal measurement sites for surface-layer experiments is difficult and constraining (National Research Council 2009). Instruments are typically mounted on narrow towers that cause minimal disturbance to atmospheric properties being measured. Such towers are usually fixed in location and this often adds geographic compromises and logistical constraints to the observation.

The CSU-MAPS observational platform for surface-layer measurements is a telescopic tower mounted on a twin-axle trailer (Fig. 1). The MAG-106 is a "cell-on-wheels" cellphone tower and is the ideal platform to mount meteorological sensors for fast-deployment scenarios. The tower is towed horizontally to the measurement site, braced with four outriggers, and leveled with seven built-in jacks. Electric winches powered by a gasoline generator then tilt the tower into the vertical and telescopically extend the five internal tower sections. Fully extended to 32 m (106 ft) unguyed, the tower is rated for winds up to 40 m s^{-1}. A guy system provides additional stability at two heights in order to reduce tower sway effects on high-frequency wind measurements. The interlocking tower sections allow for up to six cross arms that are spaced approximately 5 m when fully extended. For lower measurements, a portable 3-m tripod or 10-m aluminum tower can be deployed nearby, away from the influence of the trailer and tower base.

The instruments on each level are premounted and prewired, allowing the tower to be deployed quickly. Once on site, the tower can be fully deployed in about 30 min with two persons. Measurements include up to seven levels of wind speed and direction using sonic anemometers and temperature and humidity using thermistors and hygristors housed in passively ventilated radiation shields (Fig. 1). This includes up to two levels of high-frequency three-dimensional sonic anemometers and infrared gas analyzers to measure 10+-Hz perturbations of atmospheric CO_2 and H_2O vapor for eddy-covariance estimations of surface–atmosphere mass and energy fluxes. A four-component net radiometer provides downward- and

Fig. 2. Photographs illustrating various CSU-MAPS deployments including (a) the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) in Florida and (b) during a wildland fire research experiment in central California. CSU-MAPS was deployed simultaneously to two different research projects during 2013: (c) the Rim fire in Yosemite National Park was monitored with the truck-mounted Doppler lidar (on 26 Aug 2013) while (d) the micrometeorological tower was operating at the Burning Man event in northern Nevada to measure carbon and water vapor fluxes in the modified desert environment.

Table 1. Summary of instrumentation and sensors on CSU-MAPS

Platform/instrument	Manufacturer/ sensor/type	Variables	Measurement height	Sampling frequency
Tower	TowerWorx, Inc. MAG-106			
	CSI, CR3000 datalogger			
	CSI CR1000 datalogger			
	Gill, WindSonic	*u*, *v* winds	30.9, 21.2, 11.6, 6.5 m AGL	1 Hz
	Vaisala, Inc, HMP45C	*T*, RH	30.9, 21.2, 11.6, 6.5 m AGL	1 Hz
	Campbell Scientific Instruments, CSAT3	*u*, *v*, *w*, winds, sonic virtual temperature	Any level	10–20 Hz
	LI-COR Instruments, LI-7500	CO_2 and H_2O atmospheric gas concentrations	Any level	10–20 Hz
	Hukseflux, NR01	Up- and downwelling solar and thermal infrared radiation	Any level	1 Hz
	Delta-T, BF5	Total and diffuse beam light	Any level	1 Hz
	Hukseflux, HFP-01, Omega thermocouples	Ground heat flux and temperature	2–10-cm depth	1 Hz
Radiosonde system	Vaisala, Inc. MW31 DigiCora	Temperature, RH, pressure, altitude, winds speed, wind direction	~2–3 m AGL	1 Hz
Truck	F250 4 × 4 crew cab			
Doppler lidar	Halo Photonics, Ltd, Streamline-75	Backscatter intensity, radial velocity	18-m range gate, 80–9,600-m range	1–60 s
Microwave profiler (MPR)	Radiometrics Corp., M-3000A	Temperature, humidity, liquid water	50–250-m range gates 0–10 km	60 s
Radiosonde system	GRAW Radiosondes GmbH & Co. KG., GS-E	Temperature, RH, pressure, altitude, wind speed, wind direction	~2–3 m AGL	1 Hz
	CSI CR1000 datalogger			
	RM Young, 5103	Wind speed, wind direction	3 m AGL	1 Hz
	CSI CS215	Temperature, RH	3 m AGL	1 Hz
	RM Young, model 32500	Barometer		1 Hz

upward-directed shortwave and longwave radiation observations and the diffuse beam fraction of visible light is also measured. Heat-flow transducers and spatial-averaging soil thermocouples are used for soil heat flux, while a profile of soil thermistors and a soil-moisture-content probe measure soil temperature and water content, respectively. Acquisition, processing, and storage are handled by two data loggers, a CR3000, for the "fast data" used for eddy covariance calculations and turbulence statistics, which are sampled at 10–20 Hz and a CR1000 [both Campbell Scientific, Inc. (CSI)] for the "slow" 1-s-profile measurements. The system is powered by two deep-cycle marine batteries which are charged by a 75-W solar panel mounted on the tower.

To gain access to remote off-road sites, a 2012 Ford F250 crew cab 4 × 4 truck has been modified to not only provide towing for the tower trailer, but to also provide another instrument platform to compliment the CSU-MAPS system (Fig. 1). The truck has been outfitted with a vibration-dampening frame equipped with air bags to mount the lidar and microwave profiler in the truck bed. The air bags also provide some instrument leveling capability of approximately

3°–4° and the frame provides storage for up to three helium cylinders for radiosonde balloons. The F250 has been modified as follows. The suspension has been upgraded with a 2.5-in (6.4 cm) leveling kit for the front end and air bag springs in the rear for better trailer handling since the tower-trailer weight is 8,200 lb (~3,720 kg) and is very tongue heavy. The truck is equipped with larger and more aggressive tires for better off-road handling and clearance and is outfitted with a custom front bumper equipped a 12,000-lb (~5,445 kg) recovery winch with an integrated air compressor. The vehicle is also equipped with a standard weather station and wireless 3G router for Internet access and data transfer. Three laptop workstations are mounted in the cab with an additional Apple iPad for real-time weather data display. During deployments, data are transferred in real time to the web at www.fireweather.org.

Tropospheric profile measurements. A key capability of CSU-MAPS is tropospheric profiling using a suite of remote sensing instruments including a Doppler lidar and microwave radiometer that are mounted in the bed of the truck. In addition to the remote sensing instruments, two radiosonde systems provide in situ, upper-air measurements.

Scanning Doppler lidar. The lidar is a pulsed Doppler lidar (model Streamline 75), manufactured by Halo Photonics, Ltd., United Kingdom, that emits an eye-safe infrared light at a wavelength of 1.5 μm (Pearson et al. 2009, 2010). The system is equipped with an all-sky optical scanner enabling the lidar to scan from 0° to 360° in azimuth angle and from –15° to 195° in elevation angle. In mountainous areas, the negative scanning angle allows sampling of lower altitudes from higher terrain. There are up to 550 possible user-defined range gates at 18-m spacing with a minimum range of 80 m and a potential maximum range of 9.6 km usually associated with heavy aerosol targets such as clouds. In practice, the typical range for the system is generally about 1–1.5 km AGL based on the aerosol loading in the boundary layer. In addition to range–height indicator (RHI) and plan position indicator (PPI) scanning capability, custom scan routines can be predetermined for fast-deployment strategies, and the software allows for quick modifications to scan routines. The temporal resolution of the scans varies from a few seconds to a few minutes depending on the type of scan scheduled. Most sector scans can be accomplished in 4–6 s. It was this scanning ability that we chose this specific lidar system for CSU-MAPS. As will be shown below, all-sky custom scanning is critical for monitoring wildfire plume behavior. The lidar is also used to obtain vertical wind profiles within the ABL for general boundary layer studies.

Radiosonde sounding system. Upper-air measurements are captured using a radiosonde system for routine soundings (DigiCora MW31, Vaisala, Inc., Helsinki, Finland). The MW31 provides standard sounding data and is either mounted in the trailer cabinet during deployments or used in a desktop fashion in the field. Because the MW31 components are somewhat cumbersome, a more portable and compact radiosonde system has been permanently installed into the truck (GRAW Radiosondes GmbH & Co. KG., GS-E). The second radiosonde system provides a more mobile capability that can be used in remote areas when the truck is deployed away from the main CSU-MAPS tower.

Microwave profiling radiometer. The Radiometrics, Inc., MP-3000A is a microwave profiling radiometer (MPR) that provides continuous temperature and humidity soundings from the surface to 10 km AGL by observing atmospheric brightness temperatures in 21 K-band (22–30 GHz) channels and 14 V-band (51–59 GHz) channels (Ware et al. 2003). The vertical resolution scales with height where the highest resolution is 50 m within the ABL (Cimini et al. 2006). The MPR has an automated elevation-scanning capability and a data output period of 1 min. The MPR is fairly robust and can be deployed both on the factory tripod stand for long-term measurements at a fixed site or mounted on the truck frame when used in mobile applications. A comparison between the MPR and Vaisala, Inc., MW31 is shown in Fig. 3. While the MPR was able to capture the general evolution of the boundary layer when compared to the actual sounding made on site, it failed to capture the finescale structure and strength of the capping inversion as compared to the radiosonde. The moist layer below 500 m AGL at 0901 PST dried out when the marine-layer capping inversion broke as indicated by both the radiosonde (Vaisala, Inc., RS92-SGPD) and MPR at 1149 PST; however, the MPR dewpoint temperature is between 1° and 4°C lower than the radiosonde. It should be noted that the vertical resolution of the MPR limits its ability to capture such structure.

While the utility of the MPR may be limited for some boundary layer applications, in particular capturing inversion-height evolution, it does provide a useful tool when collocated with the lidar as intended for CSU-MAPS deployments. Figure 4 illustrates such a case during which a cold-front passage occurred while the MPR and lidar were operating continuously at San José State University. The frontal boundary is indicated by a decrease in backscatter intensity in the lowest 500 m AGL (Fig. 4a) where lower-aerosol-concentration air associated with the front intruded into the higher-aerosol-rich urban air mass. The frontal passage is also indicated by a vertically extended region of updrafts present along the frontal boundary at 2150 UTC (arrow in Fig. 4b). In the lowest 500–600 m AGL, an increase in water vapor mixing ratio obtained by the MPR (Fig. 4c) and shown by the 6 g kg^{-1} mixing ratio contour in Fig. 4a corresponds quite well to the lower backscatter intensity measured by the lidar. The ability of the MPR to provide continuous thermodynamic profiling of the boundary layer and coupled with the lidar measurements does enhance the CSU-MAPS capability. However, caution may be warranted when diagnosing finescale thermodynamic structures (i.e., Fig. 3) using the MPR alone.

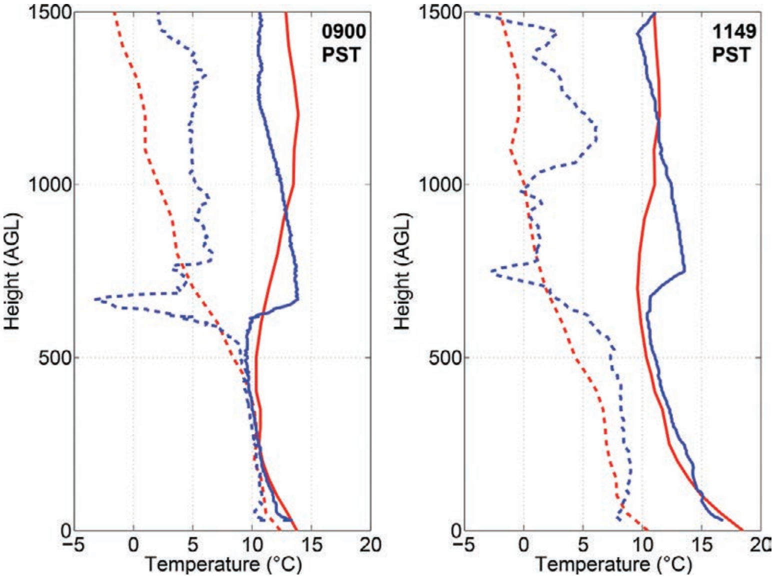

Fig. 3. Comparison profiles of temperature (solid) and dewpoint temperature (dashed) from microwave profiler (red) and Vaisala, Inc., RS92-SGPD radiosonde (blue) near Mt. Hamilton, California, on 13 Jul 2011.

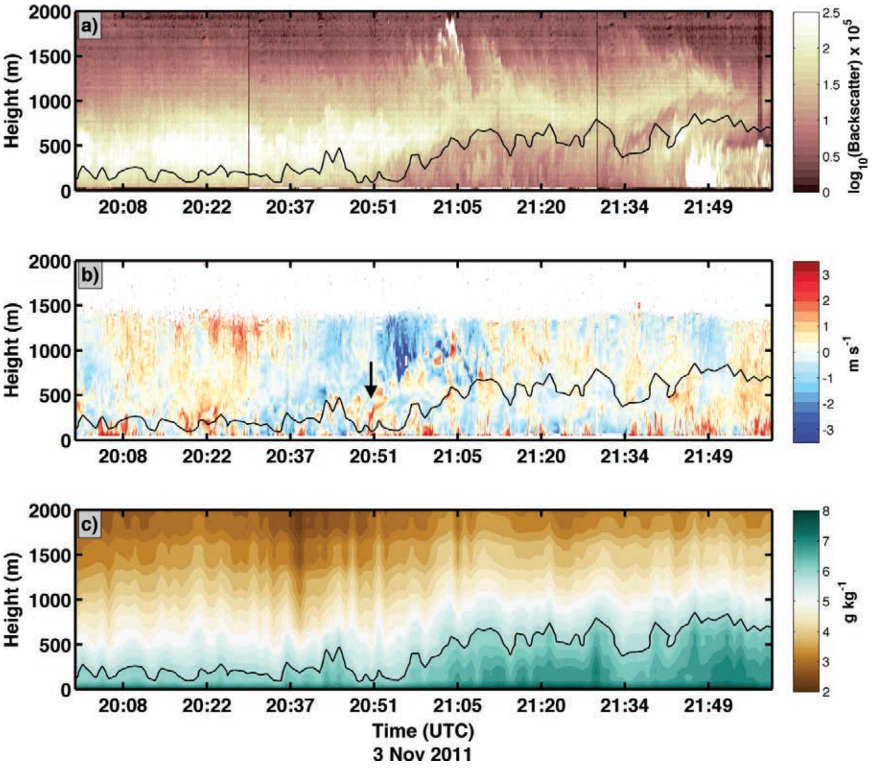

Fig. 4. (a) Lidar backscatter intensity, (b) lidar vertical velocity, and (c) MPR water vapor mixing ratio for 3 Nov 2011 measured at San José State University. Small black arrow represents the updrafts at the frontal boundary and solid line in each panel is the 6 g kg^{-1} contour of water vapor mixing ratio.

OVERVIEW OF RESEARCH APPLICATIONS.

The CSU-MAPS is designed to meet the needs of multiple institutions for a variety of experiments on surface–atmosphere interaction, including wildfire monitoring, wetland micrometeorology, wind energy prospecting, and urban energy and carbon fluxes. Instrumentation is usually deployed for relatively short-term experiments (days to months) and is scheduled via an online calendar shared among investigators. The system has been deployed to many locations throughout the United States (Table 2). The following are examples of recent research applications selected to illustrate the variety of capabilities of the system. When CSU-MAPS is not deployed for field projects, the lidar and microwave profiler operate continuously at San José State University

Table 2. Summary of CSU-MAPS deployments to date.

Date	Project/campaign	Location	Type
Jan 2011	PCAPS	Salt Lake City, Utah	Air pollution research
Apr 2011, 2012, 2013	Field class	Northern California	Education
Jul 2011	Prescribed-fire study	Northern California	Fire weather research
Jun 2012	Grass fires on slopes	Central California	Fire weather research
Jun–Jul 2012	Alpine meadow fluxes	Northern California	Micrometeorology
Nov 2012	RxCADRE	Eglin Air Force Base, Florida	Fire weather research
Jan 2013	FireFlux II	Houston, Texas	Fire weather research
May–Jul 2013	Living-roof microclimate	San Francisco, California	Urban micrometeorology
Jul 2013	Mountain fire	Hemet, California	Wildfire monitoring
Aug 2013	Burning Man event	Gerlach, Nevada	Micrometeorology
Aug 2013	Rim fire	Yosemite National Park, California	Wildfire monitoring

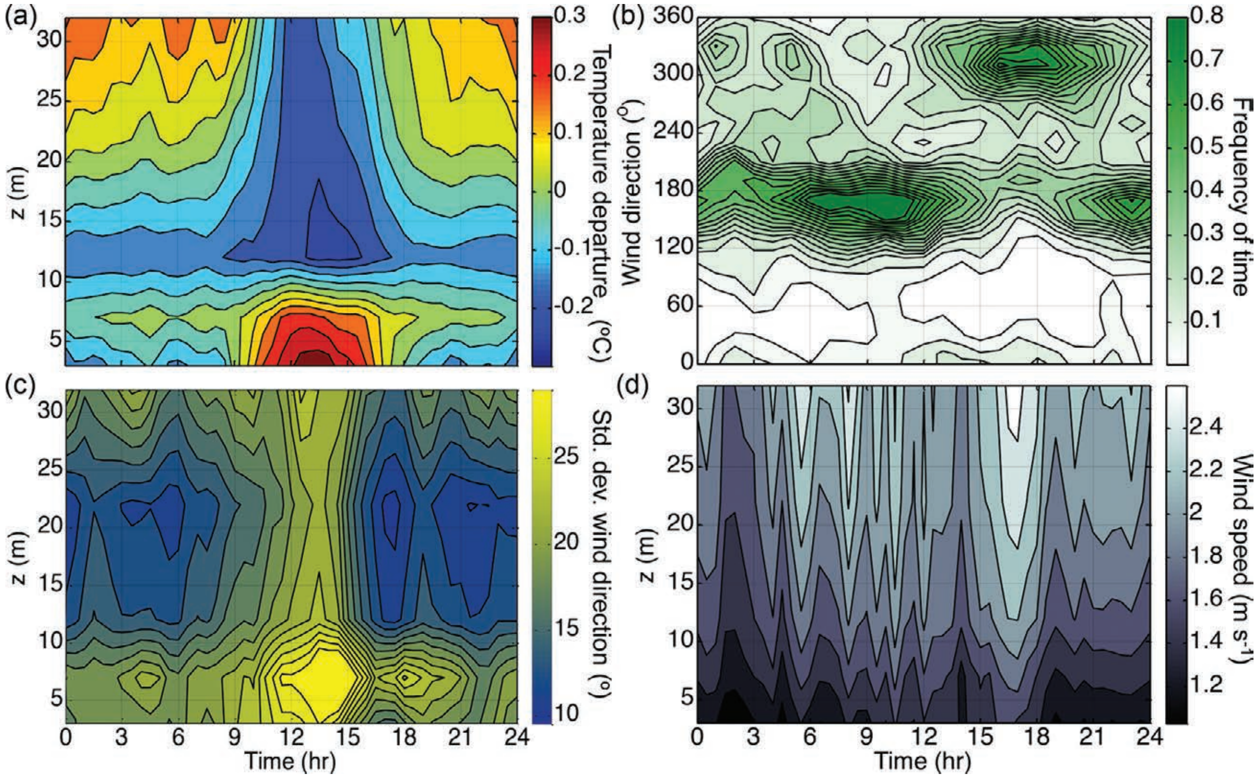

Fig. 5. Diurnal ensemble 30-min averages of observations from the CSU-MAPS tower during cold pool events in Salt Lake City, Utah, during Jan–Feb 2011, including (a) vertical profiles of the temperature departure from the profile-mean temperature, (b) wind direction frequency at 32 m, (c) profiles of standard deviation of wind direction, and (d) profiles of mean wind speed.

and San Francisco State University (Fig. 4), allowing for local mesoscale phenomena of the San Francisco Bay Area to be examined for both research and teaching purposes.

Cold air pool research. For its inaugural experimental deployment, the CSU-MAPS tower was towed to Salt Lake City, Utah, in early January 2011 to participate in the Persistent Cold Air Pool Study (PCAPS; Lareau et al. 2013). This provided the study with urban surface-layer micrometeorological information to help improve understanding of the development, evolution, and breakup of strong multiday temperature inversions that lead to poor air quality. This also provided an excellent opportunity to test the mobile micrometeorological tower component through extreme winter conditions.

Figure 5 characterizes the average diurnal surface-layer meteorology during six cold pool events [events 5–10, defined in Lareau et al. (2013)]. Through the 32-m profile there was a prevailing surface temperature inversion, which was only fully eroded for a few hours in the middle of the day (Fig. 5a). At that time, a weak superadiabatic layer developed near the surface but was very limited in depth. This is linked in time and height with enhanced turbulent mixing in this layer, based on the standard deviation of wind direction (Fig. 5c). This mixing fully extended through the profile also only for a few hours around the middle of the day. Wind direction during the experiment was downvalley (southerly) for most of the day except for a consistent midafternoon switch to an upvalley/lake breeze (northwesterly) for about 3–5 h (Fig. 5b). Wind speed profiles (Fig. 5d) also show calm stable surface-layer conditions for most of the day, with a small increase in velocity following sunrise and a diurnal peak associated with the lake breeze.

Friction velocity was generally weak throughout the day (Fig. 6a), though was strongest between 1200 and 1800 MST. This coincided initially with the peak in net radiation and sensible heat flux from 1200 to 1500 MST (Fig. 6b) followed by the stronger lake breeze from 1500 to 1800 MST (Figs. 5b and 5d). The very limited convective development from the surface on a diurnal basis means cold pools can persist for multiple days, leading to increasingly high concentrations of air pollutants near the surface. Because of the weakness of surface forcing relative to the strength of the basin-scale cold pool inversion, broader-scale disturbances are required to effectively mix out cold pools in the Salt Lake basin in winter (Lareau et al. 2013).

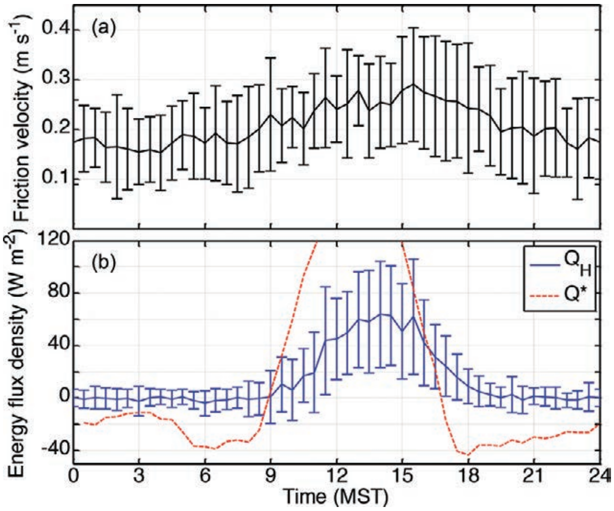

Fig. 6. Diurnal ensemble 30-min averages during cold pool events in Salt Lake City, Utah, during Jan–Feb 2011, including (a) friction velocity at 32 m and (b) energy balance components, where Q^* is net radiation and Q_H is sensible heat flux.

Fire weather research. Part of the motivation for mobility and the rapid-deployment nature of CSU-MAPS was to provide a means to study wildfires and monitor fire weather conditions during major incidents. To date, CSU-MAPS is the only meteorological measurement system with fire weather specific capability available to the wildland fire community. Since its development, CSU-MAPS has been deployed to four experimental prescribed fires and two major wildfire incidents, including the Rim fire in Yosemite National Park (Table 2). The design of the system proved adequate to move quickly and easily from different locations around the fires in order to monitor the plume structure and fire behavior from the needed angles and lines of sight. To be allowed on any wildland fire incident, whether it is a prescribed fire or wildfire, all science team members must be fire-line qualified according to the National Wildfire Coordinating Group guidelines.

The performance of CSU-MAPS in fire weather research applications has been documented in a recent preliminary study. Charland and Clements (2013) described the performance of the Doppler lidar using observations obtained during a low-intensity prescribed fire conducted in complex terrain. The evolution of the plume structure and resulting fire-induced circulations were measured and a convergence zone that consistently formed downwind of the fire front was observed. More recently, the entire CSU-MAPS was deployed during an experimental grass fire aimed to measure fire–atmosphere interactions over slopes. The lidar was placed across the valley from the experimental burn site. The fire was allowed to spread upslope through the instrumentation as a head fire, a fire that spreads with the wind, while the lidar made vertical RHI scans along the slope from an upwind location to measure circulations associated with the plume and fire front. Figure 7 shows composite images of backscatter intensity (contours) and Doppler radial velocity (color shading). At 1120 PST (Fig. 7a) the fire ignition had just begun as indicated with the low plume height. The plume tilted slightly toward the lidar (southerly) from upper-level north winds (negative radial velocities). As the fire intensified (Fig. 7b; 1125 PST), acceleration of near-surface winds into the plume was observed below 120 m AGL on the upwind side of the plume while opposing winds aloft continued to tilt the plume over

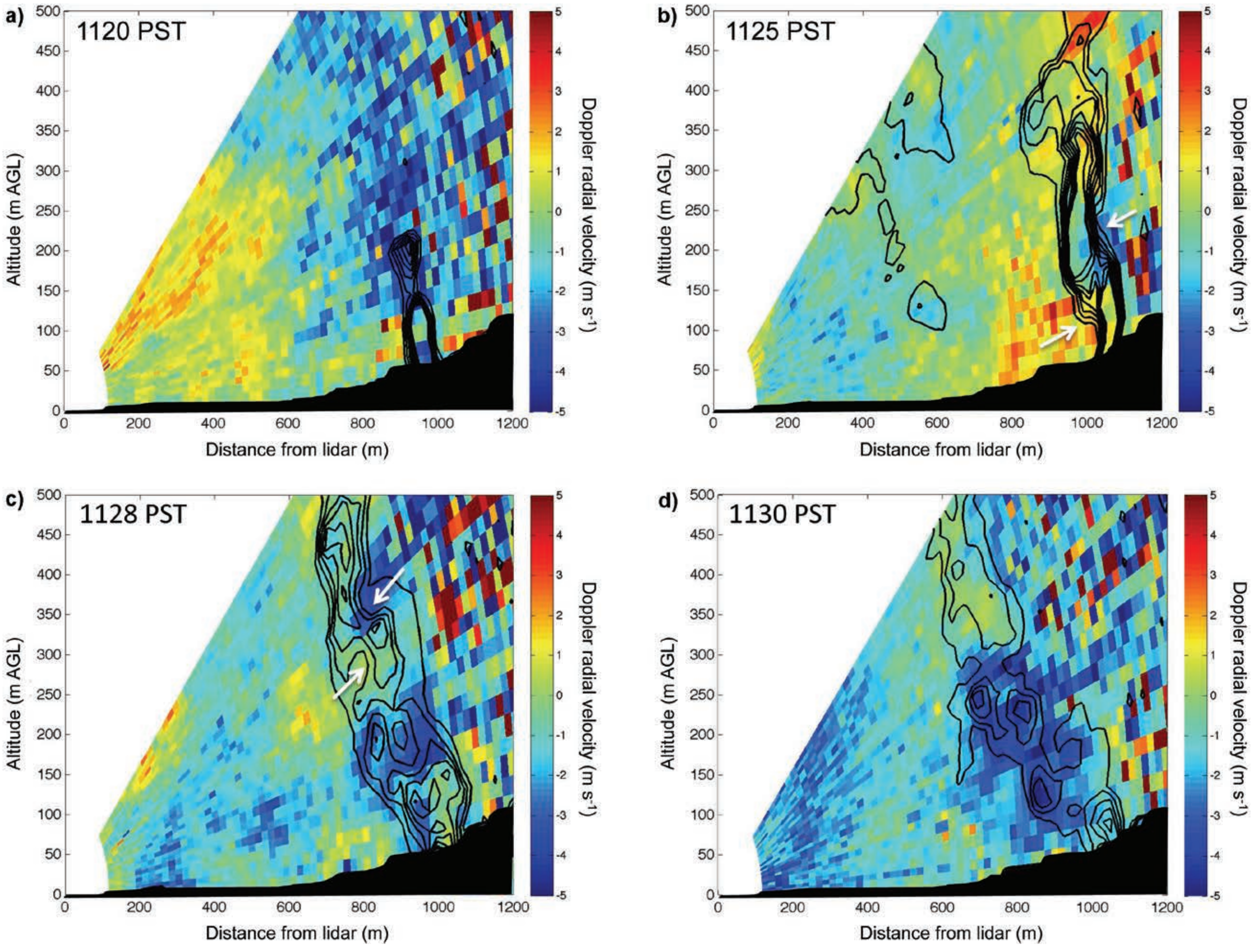

Fig. 7. Composite of Doppler radial velocity (color shading) and backscatter intensity (contours) observed during a grass fire experiment conducted at Fort Hunter Liggett, California, on 20 Jun 2012. Black shading indicates terrain. (b),(c) Small white arrows indicate circulations and regions of entrainment into the plume.

toward the south. The associated wind shear is indicated by the velocity couplet observed between 100 and 200 m AGL (arrows in Fig. 7b). Eventually, the plume rose above 500 m AGL (Figs. 7c,d). There is a distinct region of entrainment observed at 400 m AGL (Fig. 7c) where the aerosol backscatter contours tilt downward with negative radial velocity while, just below, the radial velocity is positive. This enhanced horizontal vorticity within the plume (white arrows in Fig. 7c) shows the extent of the entrainment of ambient air into the plume from aloft and indicates the relative strength of the fire–atmosphere interactions and resulting fire-induced winds. One limitation of the use of lidar in plume studies is the attenuation of the lidar beam by the smoke aerosols. This is indicated in each panel of Fig. 7 by the increased noise observed on the backside of the plume. In some situations, the lidar beam may not penetrate far beyond the backside of the plume and may not be able to fully capture the strong inflow on the downwind side of a smoke column.

Biomicrometeorology. The capability of CSU-MAPS for measuring surface–atmosphere exchanges of carbon, water and energy is useful for a wide range of micrometeorological applications. In summer 2012, the CSU-MAPS flux system was deployed on a small tower in Knuthson Meadow, a restored montane meadow at 1,520 m in the northern Sierra Nevada. The meadow ecosystem is dominated by hydric and mesic vegetation such as sedges (*Carex spp.*) and rushes (*Juncus spp.*) and was recently restored from dryland vegetation dominated by sagebrush (*Artemisia tridentata*). To counter 100 years of logging-induced gullying, small-scale damming was conducted to raise the water table several years prior to these observations. Diurnal patterns of ecosystem CO_2 exchanges and evapotranspiration (ET) over the summer period are presented in Fig. 8. At night, there was a consistent small loss of CO_2 to the atmosphere, driven by ecosystem respiration (Fig. 8a). With the onset of photosynthesis after sunrise, the flux decreased rapidly and switched from a net source to a net sink of CO_2 by 0800 PDT and reached its peak rate of productivity by 0930 PDT, after which the rate plateaued until light began to diminish in mid- to late afternoon. The apparent response of transpiration to photosynthesis is immediate (Fig. 8b), although ET continued to increase until an early afternoon peak. This suggests that water use efficiency drops significantly in the afternoon.

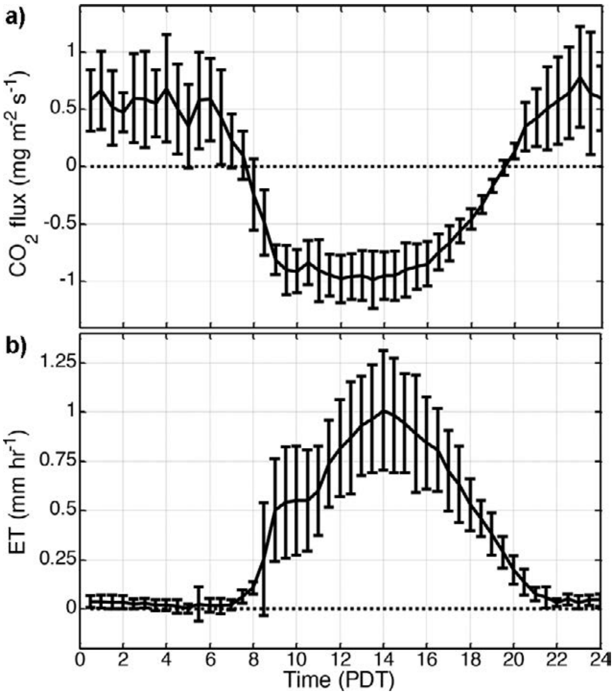

Fig. 8. Summer ensemble 30-min averages of (a) CO_2 and (b) water vapor exchanges between a montane meadow and the atmosphere, where positive numbers reflect transport from the surface to the atmosphere.

On a daily basis, the meadow ecosystem CO_2 sink averaged 4.8 gC m^{-2}, which is high when compared with wetland and grassland ecosystems on a global scale (e.g., Gilmanov et al. 2010; Lund et al. 2010) and also compared to western U.S. montane coniferous forests, which surround such meadows (e.g., Law et al. 2001). In addition, there was a daily average loss of water to the atmosphere of 8.5 mm, also high by comparison with global ecosystems. Thus the biophysical functioning of healthy meadows plays an important role in both water and carbon cycling in the headwaters of our watersheds.

CONTRIBUTION AND BENEFITS TO EDUCATION.

Field-based experiential learning in undergraduate courses in meteorology, geosciences, or physical geography is essential for cementing theoretical understanding through observation, illustrating the complexity of natural systems, understanding uncertainty in observational records, and providing students with tools to teach themselves beyond the instructor and the classroom. In addition, it blurs the boundaries between education and research and helps stimulate interest in pursuing graduate studies. There is a real challenge to providing this type of learning opportunity to large numbers of students (Schroeder and Weiss 2008; Quardokus et al. 2012; Horel et al. 2013) and to students currently underrepresented in the research community.

Fig. 9. Photograph showing students in front of the CSU-MAPS tower, with MPR on the left side and lidar on the right side. Students represent three departments from San Francisco State University and San José State University during joint field course at the Joseph D. Grant Ranch County Park, San Jose, California.

In its first three years, CSU-MAPS has provided such experiential learning opportunities in eight undergraduate courses and two graduate courses, serving more than 150 students from three departments at two California State University campuses. In addition, in this time CSU-MAPS has been used for research in six graduate student thesis projects and four undergraduate senior theses (e.g., Fig. 4).

The use of the system in classes includes both hands-on operational experiences and use of data for analysis in laboratory exercises. For example, three different "instrumentation and field methods" classes use CSU-MAPS to teach operations of measurement systems and conduct exercises such as calibration analysis and report writing. Other classes use data collected by the system to explore problems through analysis of real-world data. This includes Geog314: Bioclimatology, which uses data collected from a montane meadow (Fig. 8) to estimate daily ecosystem cycles of carbon and water.

The culmination of the educational focus is an annual spring weekend field trip for multiple classes, involving full experimental deployment of CSU-MAPS in a small mountain valley near San José, California (Fig. 9). The philosophy is to simulate a research experiment and to involve undergraduate students in all phases of the research experience, including experimental design, field deployment, manual measurements, data analysis, and presentation of results. In its first year, 50 students attended the field trip from three classes at San Francisco and San José State Universities. An online survey was conducted in order to poll students' response to experiential learning in general and this field trip in particular. Of the 28 students who replied, 26 responded that experiential learning was either a very effective (15) or effective (11) aspect of their coursework and all 28 responded that the CSU-MAPS field trip specifically was either very effective (17) or effective (11) for their learning.

SUMMARY AND CONCLUSIONS. This article has presented a novel mobile atmospheric profiling system (CSU-MAPS), capable of detailed observations of boundary layer characteristics in remote locations. The system was developed as a joint-university facility to be used by researchers and educators for a range of projects. CSU-MAPS has been tested in numerous field deployments to date and has provided detailed observations as designed. It has been particularly effective in rapid deployment situations such as for fire weather research and has operated reliably in a variety of conditions including Salt Lake City in winter, Black Rock Desert in summer, and in the vicinity of fires. Once the trailer is in position and leveled, the tower can be fully extended and operational in approximately 30 min with two persons. The CSU-MAPS has also been used in a number of university classes allowing students a hands-on learning environment and proved a very effective teaching tool according to student surveys.

Future deployments of the CSU-MAPS include a 5-yr project for wildfire monitoring in the western United States. During this project, only the truck-mounted profilers will be deployed to wildfire incidents, allowing the tower trailer to be used on other projects. Other upcoming projects include local- to regional-scale mountain meteorological phenomena, coastal fog deposition processes, and urban micrometeorology. Future deployments will capitalize on its mobility, as well as ease of use, and provide future field campaigns requiring boundary layer measurements a new facility for research and education.

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